CASNS — a heuristic algorithm for the nesting of irregular-shaped sheet-metal blanks

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This article reports on the design and implementation of a computer-aided sheet nesting system (CASNS) for the nesting of two-dimensional irregular-shaped sheet-metal blanks on a given sheet stock or coil stock. The system is designed by considering several constraints of sheet-metal stamping operations, such as bridge width and grain orientation, and design requirements such as maximising the strength of the part when subsequent bending is involved, minimisation of scrap, and economic justification for a single or multiple station operation. Through many practical case studies, the system proves its efficiency, effectiveness and usefulness.

Introduction

The advent of CADCAM has had a tremendous impact on various manufacturing sectors such as the tool and die industries. This is due to the usage of computers for the rapid creation of drawings or models, analysis and optimisation of design, and automatic generation of a tool path. Sheet-metal components form an independent family of widely used parts, ranging from consumer durables to engineering products. Kitchen utensils, typewriters, locks and computers are some of the common products that contain a large number of metal stampings. The important activity in the manufacture of these components is the design and manufacturer of die to suit the product features. Since the nesting of sheet-metal blanks constitutes the first stage of tool and die design, an attempt was made to develop a heuristic algorithm for the nesting of irregular-shaped sheet-metal blanks.

Literature review

Since the 1950s the nesting problem has received considerable attention because of the extensive use of computers, which have provided fast and economical computation, number crunching power, and the development of optimisation techniques. Most of the algorithms reported in the literature [1-5] are in the area of mathematical programming, applicable to general layout problems without pertaining to any specific application. Furthermore, their application is also restricted to the nesting of rectangular blanks. Flemings [6] developed a computer system for the nesting of sheet-metal components that is applicable when the batch size is small and the blanks are of rectangular shape, but its application is limited to flame cutting and other related applications. Adamowicz and Albano [2] developed the two-stage algorithm for irregular blanks, containing a shape-clustering stage and a rectangular layout stage. Instead of considering only one sheet layout at a time, Qu and Sanders [7, 8] developed an algorithm that considers the entire bill-of-materials at one time and lays out several sheets at the same time. They also introduced an automatic algorithm for the nesting of irregular-shaped parts, whose geometries are approximated by a composite of non-overlapping rectangles. They performed a test using a randomly generated bill-of-materials and showed that the algorithm is efficient, in terms of computation time and material usage. But, the major limitations of their algorithm are the approximation of blank geometry by non-overlapping rectangles and the assumption that good layout patterns will not be non-orthogonal. Cai Yuzu *et al.* [9] developed an expert system for the nesting of two-dimensional irregular shapes, but its application is limited to the garment industry where constraints are at a minimum. The system developed by Illeiv *et al.* [10] is also limited to the nesting of blanks whose geometry is approximated by a polygon. Nee [11] dealt with a subclass of general layout problems and developed an algorithm for the nesting of given blanks that is applicable to the sheet-metal industry. However, Nee's algorithm suffers from three major limitations; the approximation of blank geometry to a polygon, the incapability of handling blanks of different geometry, and the high computation time caused by exhaustive searching. In our present work [12, 13], we develop an heuristic algorithm for the nesting of irregular-shaped sheet-metal blanks, which is capable of handling blanks of different geometry for nesting. In our algorithm, attempts have been made to reduce the data storage requirement by changing data representation, to ensure exact representation of blank geometry without approximating to a polygon and also to reduce the computation time.

Modular structure of the system

Fig. 1 shows the modular structure of the computer-aided sheet nesting system. The functional description of various modules of the system is presented below.

- **Geometry input module:** this module gathers the geometric and technical data about the blanks. It receives interactively, in a dialogue mode, the number of blanks, the data about the blanks, the production requirement of each blank and the form of the raw material. The geometric data about the blank can be input in two ways; either in a user-friendly interactive mode by giving details of each individual entity, or by the creation of blank drawings by any standards graphics package with a data exchange facility.
- **Graphic interface module:** this module converts geometric data about blanks into its numerical form and transfers them to the database module. When blank drawings are created and transferred through the graphic editor, this module explodes the 2-D blank drawings into basic primitives such as lines and arcs, generates its numeric data and transfers

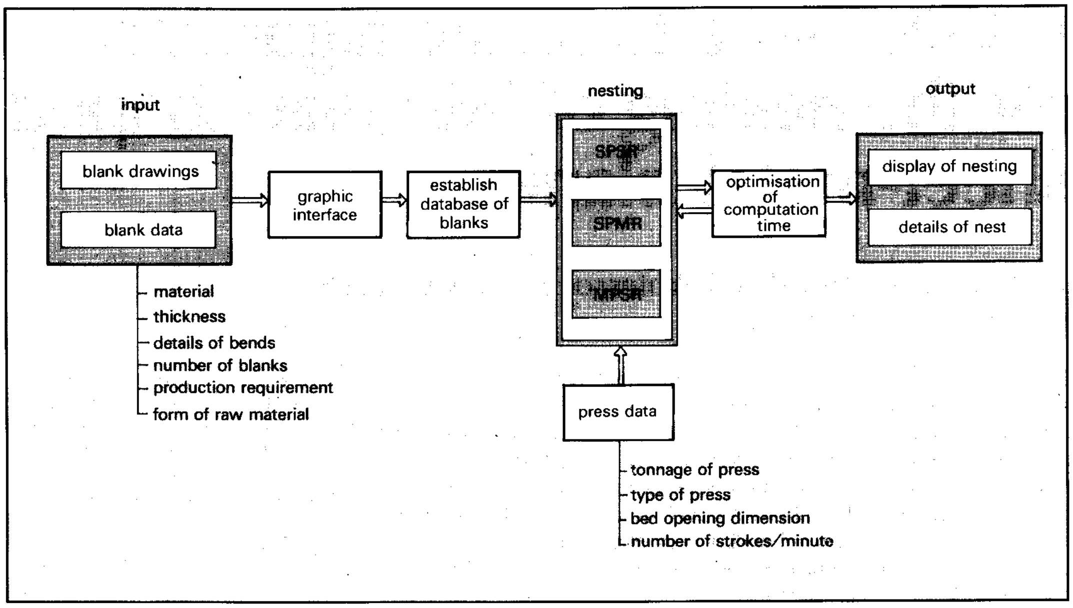

Fig. 1 Modular structure of CASNS

them to the database module. The same module is used to convert the numeric information generated by the nesting module into blank drawings.

- **Database module:** this module contains information about the blanks, presses and material properties, such as strength of material, material constant etc. It also receives information from the graphic interface module and stores it in the form of three-dimensional arrays. Each detail stored in the database has information relating to the entity, loop and blank. It also stores information about the number of blanks, production requirement of each blank, the sheet material and thickness of the sheet etc.
- **Nesting module:** this module has three further submodules, based on single-product single-row (SPSR) nesting, single-product multiple-row (SPMR) nesting and multi-product single-row (MPSR) nesting. Depending on the number of types of blanks to be nested and the available raw material, size one from the above three submodules is used by the system in nesting. The nesting module is the most important module in CASNS and is responsible for the efficiency of the layout. It extracts information about the blanks to be nested from the database module and processes the information to generate the nest details, by giving due consideration to the direction of the grain orientation and the bridge width. This module gets information from the database module and processes the information to generate the nest details. While processing, the nesting module also gets information from the optimisation module, in order to minimise the computation time by cutting down the exhaustive search of all possible alternatives.
- **Optimisation module:** the computation time depends on the complexity of the blank in terms of the number of concave vertices and the location of the concavities. This module is mainly responsible for minimising global computation time. It uses a modified one-dimensional unconstrained non-linear programming technique to minimise the computation time.
- **Output module:** this module receives data from the nesting and optimisation modules. It displays complete nesting drawings by making use of the graphic interface module. It also displays the details of nests, which include the utilisation ratio in either one or all of the processing modules, their corresponding pitch, slitting width and angle of orientation, and details of the selected press.

Design factors

□ The primary concern is to minimise wastage of material. This is more so if the quantity of blanks to be produced is large and/or if the material is expensive.

□ If there are no subsequent bending operations to follow, the blank can be rotated in any direction without due reference to the rolling direction of the sheets. The grain direction of the sheet assumes importance when a subsequent bending operation is involved. Bends should be made across the rolling direction, especially if their mechanical strength is of importance. Deviations of 45° in each way from the ideal position represent the limits of the desirable orientation. If this constraint is imposed, many good layout solutions have to be given up. If a blank contains several bends, only the most critical bend shall be considered.

□ The effect of blank layout solutions on the die design needs evaluation. The need to align the pressure centre of the blank or cluster with the axis of the press ram in order to reduce the wear in the guideways of the press is crucial. The selection of a single row layout leads to the design of simple blanking die. For pair-wise layout a double pass operation is required, if strip stock is used. If coiled stock is used, two sets of punches and dies have to be employed, as it is not practical to recoil a partially blanked coiled stock and pass it through the die opening a second time. Depending on the type of raw material, a decision will be made to select a simple or progressive die.

□ It is also necessary to consider the bridge width. Blanks located too close together or too close to the edge of the sheet tend to allow the metal to slip through the cutting edges of the punch and die. The web between the blanks that forms the scrap skeleton must be strong enough to withstand the feeding force. A softer or thinner material usually requires a larger bridge width. Bridge width is normally expressed in terms of the thickness of the sheet.

□ If the sheet-metal used is in standard lengths, the layout should be planned in such a way that the last blank at the end of the sheet is complete, with a minimum amount of stock leftovers. For coil stock this requirement is not essential.

□ Blank layout also takes into consideration the press capacity available. Multiple blanking requires a larger press bed area, as well as blanking force.

□ Single-row blanks are produced individually with each press stroke. In this arrangement, every blank has identical orientation with respect to one another. Blanks are very often produced in multiple quantities, typically two or more per press stroke. Multiple blanking often requires the blanks to be orientated at different angles to one another. A typical blank layout often permits a pair of blanks to be oriented at 180°. This arrangement often improves the layout. However, if blanks are turned upside down, the burr formed may give some problem in use. By multiple blanking, even though the production rate is increased, the economics of the process can only be justified if the quantity to be produced is large enough to offset the increase in tooling cost.

□ Coil stock is used for high-volume production. The use of expensive accessories, such as straighteners, recoilers and decoilers, is only then justified.

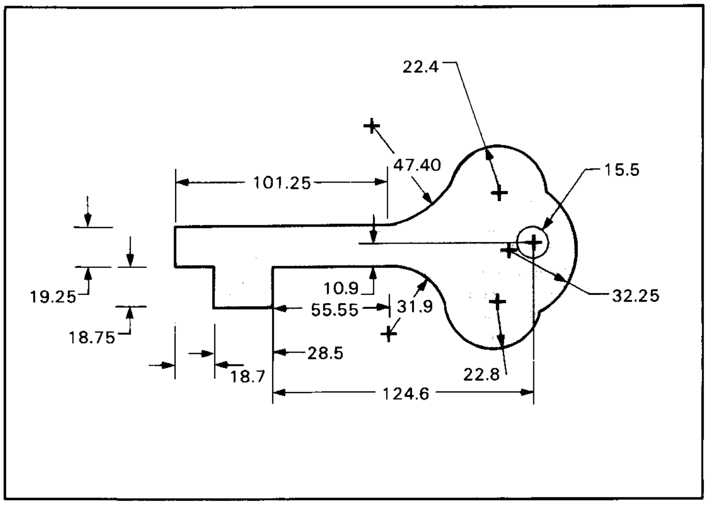

Fig. 2 Detailed drawing of a blank for nesting

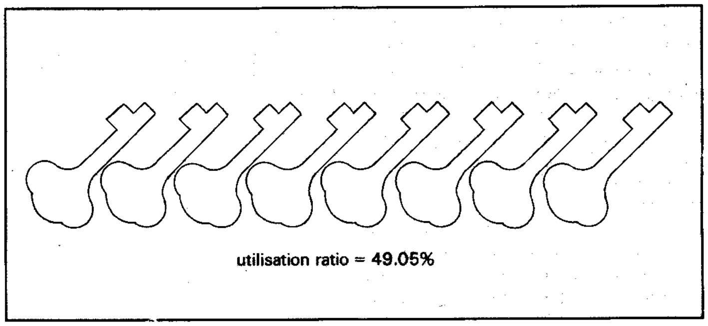

Fig. 3 Best utilisation ratio of SPSR nesting with uniform orientation

Blank geometry representation

The input of the component geometry can be given through any standard graphics package. An arbitrary two-dimensional shape can be divided into elements such as line segments, arc segments and circles. An interface was developed that explodes the blank profile into basic entities such as line, arc and circle. The system stores co-ordinates of start and end points for line entities, co-ordinates of the centre point, start point and end point for the arcs and centre, and radii for circles. A facility is also provided in the system to represent a spline by a set of data points, which act as control points for the spline. A two-dimensional shape consists of one external feature and several internal features. Initially, only external feature information is considered for nesting, since the internal features may not affect the nesting process. As soon as the input process of blank drawing is completed, a digital representation of the blank is created, which contains types of geometrical elements, node co-ordinates, the number of features and entities etc.; it is stored in a data file which will be used for the subsequent processing in the system.

The nesting algorithmic approach

The input for the nesting algorithm consists of the digital representation of the blank created by the graphic interface module. The production requirement of each blank, the available raw material size, the properties of sheet material and details of available presses and other

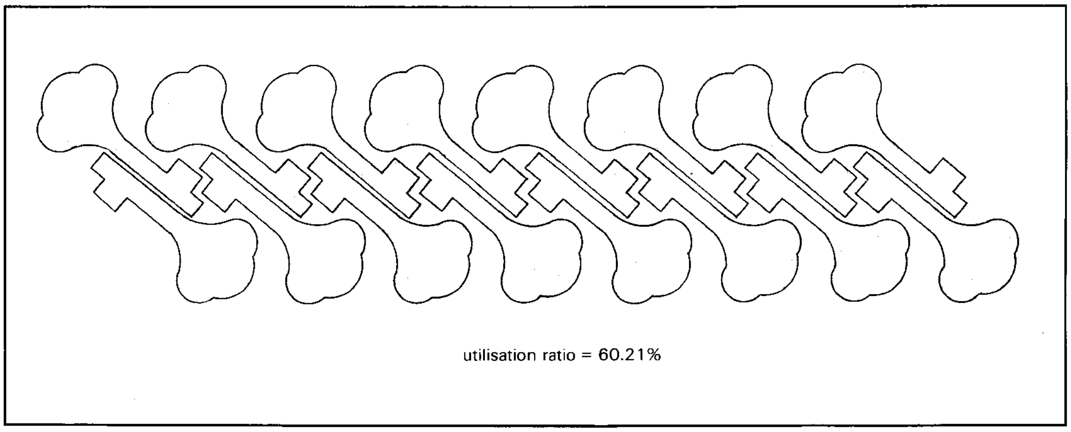

Fig. 4 Best utilisation ratio of SPSR nesting with half-turn rotation (pair-wise cluster)

related parameters are extracted from the database module. Depending on the number of blank geometrics to be nested and the form of available raw material, one of the three algorithms SPSR, SPMR, and MPSR is used by the system.

The algorithm SPSR is called by the CASNS system when there is no stock-width constraint for the given raw material. In this algorithm, two approaches are implemented. The first approach is the uniform orientation (traditional) approach, in which the blank is reorientated in a counter-clockwise direction at various angles between 0° and 180° and placed side by side, by giving due consideration to bridge width and grain orientation. The second approach is half-turn rotation, which generates a cluster of the blanks. In this approach, each cluster consists of an original blank, with optimum orientation, and another blank that is rotated by 180° with respect to the mid-point of the longest edges of the first blank. The second approach is usually more efficient than the uniform orientation approach. If the two blanks of a pair-wise cluster are overlapping, the system shifts the second blank by a predetermined distance in all directions until the overlapping is completely cleared. If there is no subsequent bending of blanks involved, the layout solution with the highest utilisation ratio will be treated as the best layout. If subsequent bending of blanks is involved, the SPSR algorithm identifies the range of orientation, which affects subsequent bending based on input information such as the bend angle, eliminates the orientation in that range, while reorientating the blank, and calculates the utilisation ratio.

The algorithm SPMR is called by the system when the given raw material is of a sheet stock with finite dimensions. In this algorithm, both the uniform orientation approach and half-turn rotation approach are also implemented. The SPMR algorithm treats the selected cluster as a composite blank and reorientates between 0° and 180° in order to identify the optimal orientation of the blank. The selected cluster is further packed on the given sheet stock by giving due consideration to grain orientation and bridge width to arrive at the final layout. For the calculation of the utilisation ratio, the SPMR algorithm considers the wastage on all four sides of the sheet.

The algorithm MPSR is called by the system when the number of blank geometries to be nested is more than one and the given raw material is without stock-width constraint. Before starting the actual nesting process, the system calculates the area of all the blanks to be nested and arranges them in descending order. It selects a blank with the largest area and sets the orientation of the blank at the initial position and marks its longest boundary edges, connecting the convex vertices as pivot edges. Then the algorithm selects the blank with the second largest area and tries to reorientate it about the pivot edges of the first blank. If the blanks are overlapping, then the second blank will be shifted by a predetermined distance until the overlapping is completely cleared, and the utilisation ratio will be calculated. The process will be repeated about all the pivot edges of the first blank. Then the selected cluster is treated as a composite blank, and its new pivot edges will be marked. This complete process will be repeated until all the blanks are nested. The final selected cluster is reorientated between 0° and 180° in order to find out the orientation of the cluster corresponding to the highest utilisation ratio.

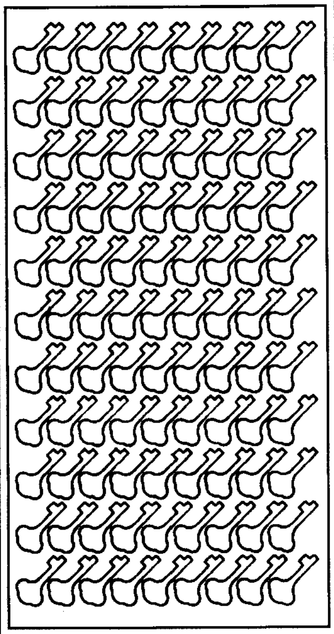

Fig. 5 Best utilisation ratio of SPMR nesting with single blank

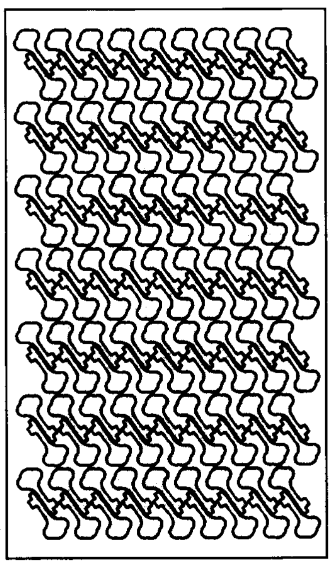

Fig. 6 Best utilisation radio of SPMR nesting with pair-wise cluster

The procedure presented above will be used to produce clusters of more than two blanks by approaching the multiple-shape clustering problem as a multi-stage pair-wise clustering problem. Initially, the algorithm finds the optimal clustering of two shapes and combines the two shapes to form a composite shape. Then, it combines the optimal clustering of the composite shapes with another shape and forms a new composite shape. This procedure will be repeated until all the blanks are exhausted. However, due to memory limitations, the present algorithm is tested for a maximum number of three blank geometries. One of the major limitation of this algorithm is that (since the blanks are clustered in stages and there is no provision for backtracking to reposition the shapes) the algorithm may not guarantee that the optimum clustering of the shape will be attained.

Case study

The system is implemented on an Apollo (Nexus-3000) workstation, which s a 32-bit minicomputer with an Motorola 68020 series CPU with 4 MB of main storage memory. The system is implemented in Fortran 77 under an AEGIS environment in a highly interactive manner. A sample blank to be tested on the system is shown in Fig. 2. The details of the external features of the blank are considered for the process of nesting only, since the internal features do not affect the process of nesting. For SPSR nesting, the best utilisation ratio without stock-width constraint is shown in Figs. 3 and 4. For SPMR nesting, the best utilisation ratio with stock-width constraint is shown in Figs. 5 and 6. For MPSR nesting, the best utilisation ratio for two different blank geometrics without stock-width constraint is shown in Fig. 7. Fig. 8 shows the numerical output of the computer-aided sheet nesting system, dimensions of the selected sheet stock and the utilisation ratios of the three sub-algorithms.

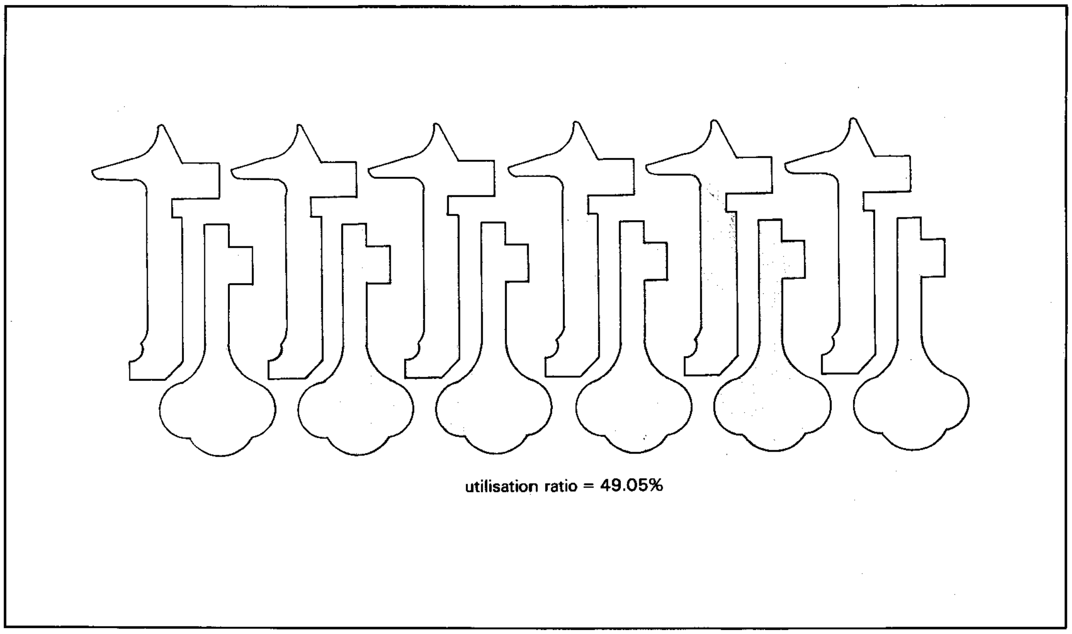

Fig. 7 Best utilisation ratio of MPSR with two different blanks

Optimum angle of orientation	=41°
Area of the blank	=8012.1875
Slitting width of single nest	=177.5625
Pitch of single nest	=91.9875
Utilisation ratio of single nest	=49.05%
Slitting width of pair-wise cluster	=245.16
Pitch of pair-wise cluster	=108.55
Utilisation ratio of pair-wise cluster	=60.21%

Results of SPSR algorithm

Length of the sheet	=1875
Width of the sheet	=1000
Area of the blank	=8012.187
Optimum angle of orientation for single nest	=41°
Total number of blanks nested	=99
Utilisation ratio with single nest	=42.30%
Optimum angle of orientation for pair-wise cluster	=36°
Total number of blanks nested	=126
Utilisation ratio of pair-wise cluster	=53.84%

Results of SPMR algorithm

Optimum angle of orientation	=90°
Area of blank 1	=8012.1875
Area of blank 2	=7947.875
Slitting width of the cluster	=112.5675
Pitch of the cluster	=289.0575
Utilisation ratio	=49.05%

Results of MPSR algorithm

Fig. 8 Output of CASNS

Conclusion

The CASNS is implemented on an Apollo (Nexus-3000) workstation, in Fortran 77. An interface was developed between a standard graphics environment and CASNS by using 2-D graphic metafile resources, which is a powerful graphics utilities set available on the Apollo system. The system was extensively tested for a large number of components manufactured in various sheet-metal industries. Through many practical case studies, the system proved its efficiency, effectiveness and usefulness. At present, an attempt is being made to develop an integrated system for die design, from the flat pattern development stage to the final stage of die component selection and design.

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